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Experimental Overview of High p_T Results at RHIC

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High transverse momentum (p_T) particles, originating from hard-scattered partons, hold the promise of probing the medium created in heavy-ion collisions. In the last 7 years, the Relativistic Heavy Ion Collider (RHIC) has provided a wealth of high p_T probes. An overview of high p_T results from RHIC will be presented with a focus on what is not yet understood. Our current understanding of parton energy loss from single-particle measurements will be reviewed, including what has been added to our (possible lack of) understanding from more recent heavy-flavor results. Di-hadron correlation measurements have provided more differential information to help understand the modification of jets due to the medium, but can be interpreted as being only from surface emission, which questions the value of high p_T particles as true *probes* of the medium. The future of photon-hadron correlation measurements, in conjunction with the di-hadron measurements, will hopefully add to our understanding of the energy loss mechanism.

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1. What have we learned from single-particle spectra?

Since RHIC began operation in 2000, the data from the first run already indicated large effects of dense matter on the particle spectra at high transverse momenta (p_T) [1]. A large suppression (factor of 4-5) was observed in the yield of neutral pions and charged hadrons at high p_T, as measured by the nuclear modification factor, which is defined as

$$\begin{aligned} R_{AA}(p_T) &= \frac{\text{Yield per A + A collision}}{N_{binary} \times (\text{Yield per p + p collision})} \\ &= \frac{d^2N^{A+A}/dp_T\, d_\eta}{(N_{binary})(d^2\sigma^{p+p}/dp_T\, d_\eta)/\sigma^{p+p}_{inelastic}} \\ &= \frac{d^2N^{A+A}/dp_T\, d_\eta}{(T_{AA})(d^2\sigma^{p+p}/dp_T\, d_\eta)} . \end{aligned}$$

Figure 1 shows R_{AA} for π^0 and η mesons as well for photons, measured by the PHENIX experiment [2]. The data show a similar suppression pattern for the π^0 and η, which appears to be a nearly constant factor of approximately 5 for p_T greater than 4 GeV/c, while no suppression is observed for direct photons.

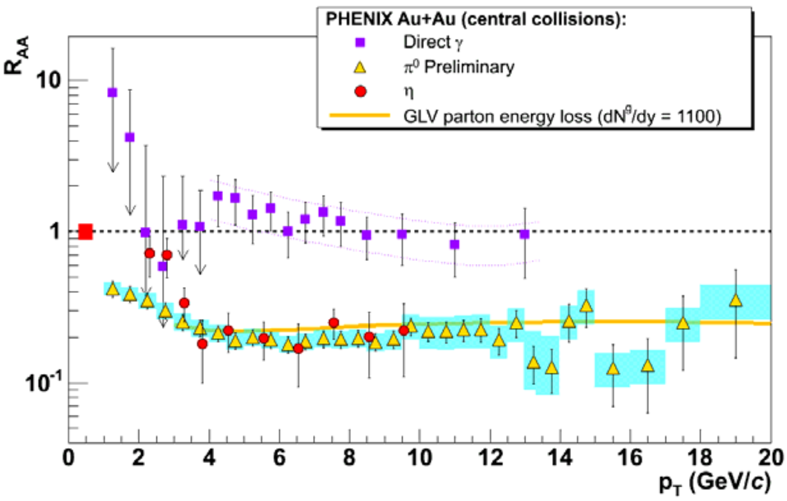

Figure 1. *Nuclear modification factor as a function of p_T for π^0, η, and direct photons measured by the PHENIX experiment.*

This data can be described by theoretical calculations of parton energy loss in the matter created in Au+Au collisions [3-5]. From these theoretical frameworks, we have learned that the gluon density dN_g/dy must be approximately 1000 [6], and the energy density of the matter created in the most central collisions must be approximately 15 GeV/fm^3 to account for the large suppression observed in the data [7].

The observation that R_{AA} is approximately flat for p_T greater than 4 GeV/c leads to a simple picture in which the energy loss is a constant fractional value of the energy of the parton [8]. In such a "model" one can calculate the effective fractional energy loss S_{loss} as a function of the centrality of the collision (shown in Fig. 2). In the most central collisions, the effective energy loss is approximately 20%.

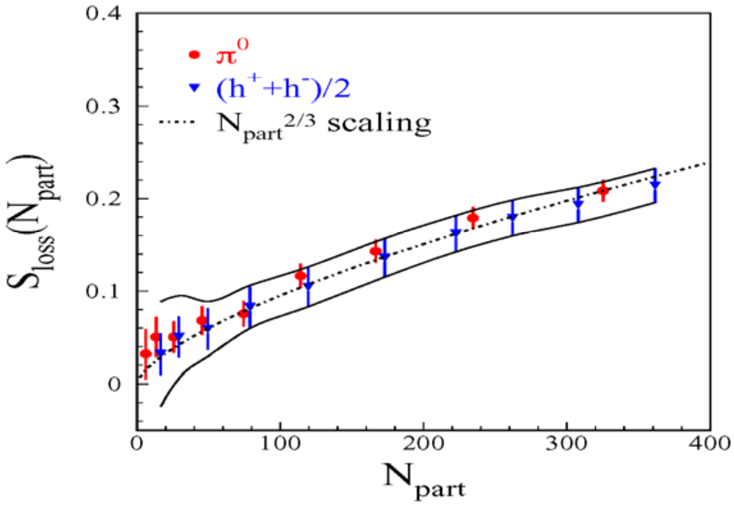

Figure 2. *Fractional energy loss Sloss as a function of the number of participants Npart (or the centrality of the collision).*

A shortcoming of single-particle measurements is that there is likely a large surface bias in which the majority of the surviving hadrons with a large p_T come from hard scatterings near the surface of the reaction zone, while few of them come from hard-scattered partons from deep within the reaction zone. In order to do true "jet tomography" [9] using high p_T probes, one needs access to the jets that come from hard-scattered partons that actually *probe* the densest part of the reaction zone. In the following sections, other measurements of high p_T probes will be discussed with the goal of better understanding parton energy loss in the dense matter created in heavy-ion collisions. In particular, heavy-flavor and di-hadron correlation measurements will be shown. The future of photon-hadron correlations will be discussed as well.

2. Heavy-Flavor Suppression

More recently, PHENIX and STAR have measured the suppression of heavy-flavor (charm and bottom mesons) at high p_T through non-photonic electrons [10, 11]. Surprisingly, R_{AA} for the non-photonic electrons is nearly as small as for the light mesons (π^0, η, K^0_s, etc.). Figure 3 shows R_{AA} for non-photonic electrons measured in central Au+Au collisions, compared with various theoretical calculations [12-15], and in d+Au collisions. The suppression of heavy mesons has been difficult to describe using the same theoretical framework, with the same conditions, as was used to describe the suppression of the light hadrons [12]. This has led to a re-evaluation of the energy loss mechanism (gluon bremsstrahlung vs. elastic scatterings or some combination thereof) responsible for the suppression even of the light mesons, which was originally believed to be dominated by gluon bremsstrahlung. On the other hand, it is not impossible that the mechanism for heavy-quark energy loss is different from that of light-quark (and gluon) energy loss [16]. In conclusion, the dominant mechanism for energy loss, elastic and/or radiative, is not well understood.

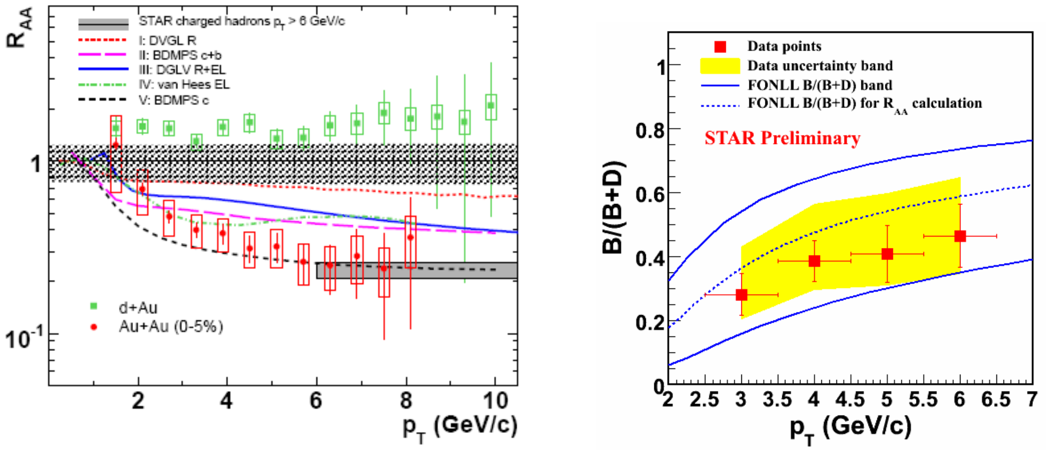

Figure 3. *The left plot shows RAA measured for non-photonic electrons in central Au+Au collisions and d+Au collisions [11]. The right plot shows the contribution of bottom to the heavy-flavor measurement [17].*

3. Di-hadron Correlation Measurements

In heavy-ion collisions at RHIC, direct identification of jets is not straightforward due to the large event multiplicities. However, jets can be studied on a statistical basis by measuring a two-particle correlation in the angle of an associated particle with respect to the trigger particle.

3.1 "Disappearance" of the Away-Side Jet

The first measurement of the away-side jet modification at RHIC came from the STAR experiment using trigger particles with p_T between 4 and 6 GeV/c and associated particles in various p_T bins below 4 GeV/c [18]. This measurement showed that the away-side yield decreases with increasing centrality, leaving no significant yield for the most central Au+Au collisions. Figure 4 shows the suppression of the away-side jet yield for central Au+Au collisions. This measurement is consistent with the picture of a surface bias in which the trigger particle is produced near the surface of the reaction zone, while the away-side jet is absorbed by the medium.

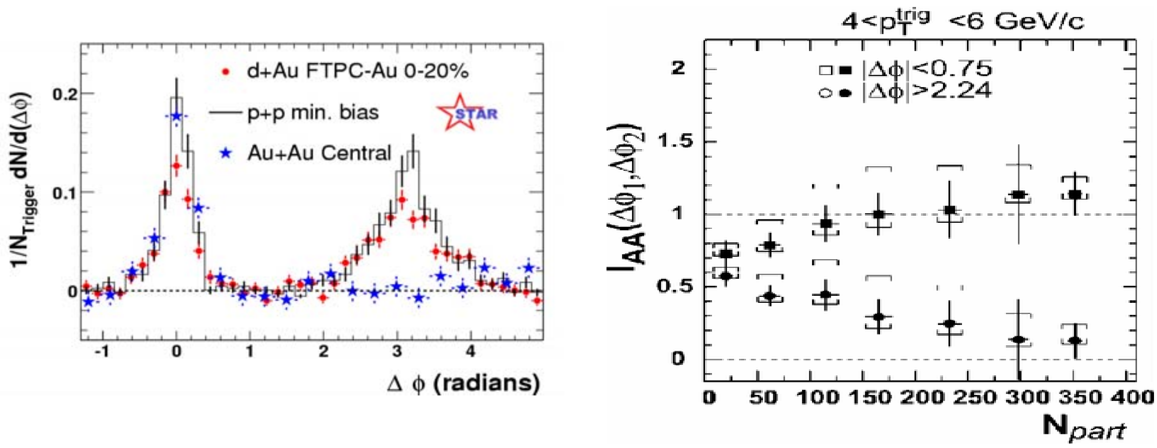

Figure 4. *Two-particle angular correlation measurements [18]. The left plot shows the angular correlation between a trigger particle with p_T between 4 and 6 GeV/c and an associated particle with p_T greater than 2 GeV/c and less than the p_T of the trigger particle. The non-correlated background as well as the flow background have been subtracted. The right plot shows the ratio of the jet-correlated yield in Au+Au to the jet-correlated yield in p+p collisions as a function of N_{part}. The upper data points represent the near-side yields, while the lower represent the away-side yields.*

3.2 "Reappearance" of the Away-Side Jet

The observation of an away-side suppression in the two-particle correlation measurement prompted both PHENIX and STAR experiments to study the correlation function in more detail as a function of both the trigger p_T and the associated particle p_T [19, 20]. At sufficiently high trigger p_T, the away-side jet reappears, although suppressed in strength [21]. Figure 5 shows the evolution of the correlation function with increasing p_T(trig) and increasing p_T(assoc). The background is not subtracted in these plots, but becomes less significant with increasing p_T. A peak on the away-side for the highest p_T bins is clearly visible even without any background subtraction. This suggests that some of the jets with p_T exceeding 6 GeV/c, or so, indeed escape the dense medium. On the other hand, a comparison to the d+Au data reveals that, although the away-side yield in central Au+Au is still suppressed at these large values of p_T, the width of the away-side peak does not seem to be modified in central Au+Au collisions. This may be due to a bias in which only tangentially produced jets (in which both near-side and away-side are near the surface) are observed, while those produced within the medium are again completely absorbed. Some theoretical calculations, which include the energy loss of hard-scattered partons within the bulk matter that is itself evolving (e.g. hydrodynamically), give hope that the surface bias in these di-jet measurements is not so extreme [22].

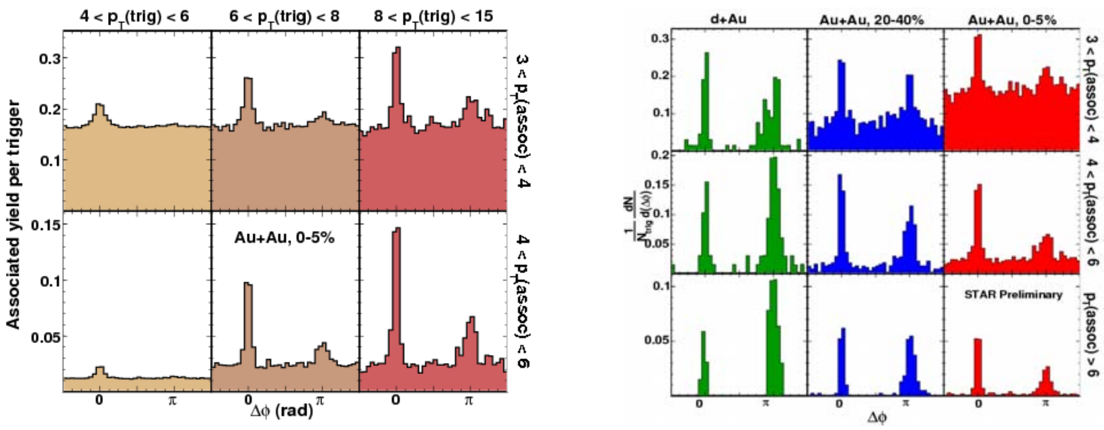

Figure 5. *Angular correlation function ($1/N_{trig}$) $dN/d(\Delta\varphi)$. The left plot shows the evolution of the associated yield with increasing p_T(trig) and p_T(assoc) for the most central Au+Au events. The right plot shows a comparison of the correlation function in d+Au 20-40% Au+Au and 0-5% Au+Au events for 8<p_T(trig)<15 GeV/c and increasing p_T(assoc).*

4. The Future of Photon-Hadron Correlations

The correlation measurement of a direct photon with hadrons (γ-jet) has been considered the "golden probe" of the dense matter created in heavy-ion collisions [23]. Since the photon does not interact strongly with the medium, it provides a clean measure of the energy of the jet produced together with the photon in the initial hard scattering. Any modification to the jet on the away-side of the trigger photon is a direct handle on the modification due to the medium. This measurement, however, requires a large amount of statistics. The dominant source of photons is hadronic decays, making it difficult to extract the *direct* photon-hadron correlation signal. The advantage in Au+Au collisions is the suppression of hadrons at high p_T, increasing the ratio of signal photons to background photons with increasing centrality. According to measurements of direct photons in Au+Au collisions, the ratio of direct photons to background photons is 1:1 at p_T of approximately 7 GeV/c in the most central Au+Au collisions [24] (almost an order of magnitude better signal to background than in p+p collisions at the same p_T). The correlation function for direct-photon triggers with associated hadrons should show nearly no near-side yield, while the away-side yield measures the modification of the jet due to the medium. Figure 6 shows some initial attempts by both PHENIX and STAR to extract a correlation function for γ-jet. The result in the left plot [25] does not include a subtraction of the correlation function of the background photons. However, by simply increasing the centrality of the Au+Au collision, it is observed that the strength of the near-side correlation decreases. Since this follows the expectation for an increasing purity in direct photons, it is evident that increasing the centrality selection improves the ratio of direct photons to background photons in the trigger sample. The result in the right plot is truly the *direct* photon-hadron correlation, after having subtracted the correlation function of background photons (from neutral pion decays) with hadrons. The statistical errors are still too large to make strong conclusions about the result. A possible alternative to measuring the inclusive photon-hadron correlation function and subtracting the background photon-hadron correlation function is to select a "cleaner" sample of direct photons, separating the background photons using the shower shape in the shower-maximum detector within the STAR barrel electromagnetic calorimeter [26]. In this case, one still needs to subtract the remaining contribution from background photon-hadron correlations.

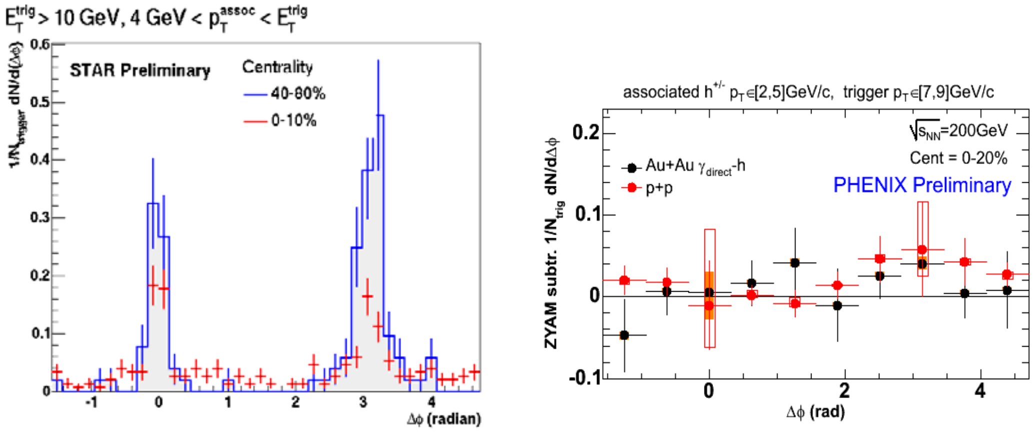

Figure 6. *First measurements of photon-hadron correlation function by STAR (left) and PHENIX (right).*

In addition to the challenge of the measurement itself, the interpretation of the measurement will pose further challenges. If the surface bias is now imposed on the away-side jet, then the surviving yield of hadrons will still provide us very little information via "tomography" of the medium.

5. Conclusions

We have learned that the medium created in central Au+Au collisions at RHIC must be extremely dense for hard-scattered partons to lose enough energy to lead to the observed suppression in the yield of hadrons at high p_T. However, the dominant mechanism for the energy loss, responsible for the suppression observed in the light hadrons as well as for the heavy flavor, is not yet understood. Di-hadron correlation measurements have improved our qualitative understanding of jet modifications due to the dense medium. However, a quantitative description of the observed jet modifications is yet to be provided from theoretical calculations. Furthermore, the observed away-side jet correlation at high p_T (p_T>6 or 8 GeV/c) shows no evidence of modification from the parton having traversed the medium, *i.e.* no modification of the width of the correlation with increasing centrality. The yield of the away-side correlation is suppressed, but this can be explained by a measurement bias toward tangential emission only. The di-hadron correlations can hopefully be best understood in conjunction with measurements of the direct γ-jet correlation, where the bias would at least be different. For this measurement, a large statistics data set is required.

References

[1] K. Adcox *et al*. (PHENIX), Phys. Rev. Lett. **88**:022301, 2002.

[2] S.S. Adler *et al*. (PHENIX), Phys. Rev. Lett. **96**:202301, 2006.

[3] I. Vitev and M. Gyulassy, Nucl. Phys. A**715**, 779-782 (2003).

[4] X.-N. Wang, Phys. Lett. B**595**, 165-170 (2004); X.-N. Wang, Phys. Lett. B**579**, 299-308 (2004).

[5] C.A. Salgado and U.A. Wiedemann, Phys. Rev. D**68**:014008, 2003.

[6] I. Vitev and M. Gyulassy, Phys. Rev. Lett. **89**:252301, 2002.

[7] I. Vitev, J. Phys. G**30**, S791-S800 (2004).

[8] S.S. Adler *et al.* (PHENIX), nucl-ex/0611007.

[9] M. Gyulassy, P. Levai and I. Vitev, Phys. Lett. B**538**, 282-288 (2002); E. Wang, X-N. Wang, Phys. Rev. Lett.**89:**162301, 2002.

[10] S.S. Adler *et al.* (PHENIX), Phys. Rev. Lett.**96**:032301, 2006.

[11] B.I. Abelev *et al.* (STAR), Phys. Rev. Lett. **98**:192301, 2007.

[12] M. Djordjevic *et al*., Phys. Lett. B**632**, 81 (2006).

[13] N. Armesto *et al*., Phys. Lett. B**637**, 362 (2006).

[14] S. Wicks *et al.*, nucl-th/0512076.

[15] H. van Hess, V. Greco and R. Rapp, Phys. Rev. C**73**:034913, 2006.

[16] A. Adil and I. Vitev, arXiv:hep-ph/0611109.

[17] X. Lin for the STAR Collaboration, arXiv:nucl-ex/0701050.

[18] C. Adler *et al*., (STAR), Phys. Rev. Lett. **90**:082302, 2003.

[19] J. Adams *et al*., (STAR), Phys. Rev. Lett. **95**:152301, 2005; M.J. Horner for the STAR Collaboration, arXiv:nucl-ex/0701069.

[20] S.S. Adler *et al*. (PHENIX), Phys. Rev. Lett. **97**:052301, 2006.

[21] J. Adams *et al.* (STAR), Phys. Rev. Lett. **97**:162301, 2006.

[22] T. Renk and K.J. Eskola, Phys. Rev. C**75**:054910, 2007.

[23] X.-N. Wang *et al.*, Phys. Rev. Lett. **77**, 231-234 (1996).

[24] S.S. Adler *et al*. (PHENIX), Phys. Rev. Lett. **94**:232301, 2005.

[25] T. Dietel for the STAR Collaboration, Nucl. Phys. A**774**, 569-572 (2006).

[26] J. Jin for the PHENIX Collaboration, arXiv:0705.0842.

[27] S. Chattopadhyay for the STAR Collaboration, Nucl. Phys. A**783**, 591-594 (2007).